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LCA FOR ENERGY SYSTEMS

Life cycle analysis on the design of induction motors

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Abstract

Purpose Herein is reported an application of life cycle analysis (LCA), using the Methodology for the Ecodesign of Energy Using Products (MEEUP), in order to assess the influence of some design parameters in the environmental impact of three-phase induction motors. A motor design procedure to minimize the total environmental impact, based on data obtained from commercial motors, is presented. This procedure is specially intended for the low power range due to the greater potential for energy savings in motors having an output power of 0.75 to 4 kW.

Methods A procedure has been developed, based on previously acquired data, to determine the parameters required for application of the MEEUP methodology. These comprise the quantity of each of the motor's main constituent materials used in the production phase, and the two operating variables that directly influence the LCA results: output power and efficiency.

Results and discussion The procedure was applied to two 1.5 kW induction motors of different efficiency (according to standard IEC60034-2-1). The calculation results were compared satisfactorily with the laboratory test results. The total environmental impact of the two real motors and of the proposed motor was determined in the production, service life, and end-of-life phases.

Conclusions Given the potential for energy savings in electric motors, LCA-based environmental impact assessment should be incorporated into motor design.

Keywords Efficiency · Environmental impact · Induction motor · Life cycle · Losses

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1 Introduction

Induction motors are currently the most widely used electric motors in industry. Improving the efficiency of these motors would enable significant energy savings over their service life. As outlined in standard IEC60034-30 (IEC 60034–30 2007; De Almeida et al. 2011, Fig. 1), the greatest potential for energy savings is for motors having an output power of 0.75 to 4 kW.

To assess the environmental impact of energy-using products, the European Union developed directive 2005/32/EC (European 2005), which it has extended to energy-related products, through directive 2009/125/EC (European 2009). Based on studies presented mainly in the report EUP Lot 11 Motors (De Almeida et al. 2008), specifications for the ecodesign of electric motors have been set in the European Commission Regulation EC 640/2009 (European Commission 2009). This regulation indicates the minimum efficiency necessary to meet the specifications for the ecodesign of electric motors (categories IE1, IE2, and IE3, specified in standard IEC60034-30), in an attempt to harmonize the different efficiency categories for motors having the following characteristics: two, four, or six poles; 50 or 60 Hz; rated voltage of 1,000 V; and rated power of 0.75 to 370 kW (Fig. 2 shows these categories for four-pole, 50-Hz motors). In the European Union, this classification has

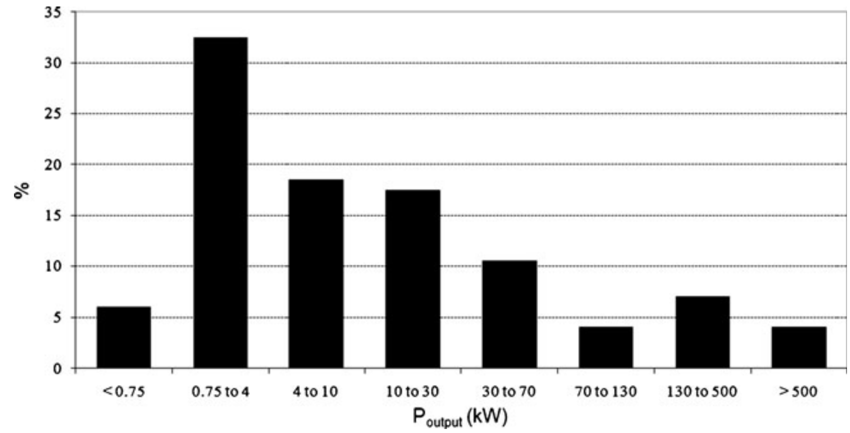


Fig. 1 Potential (as percent) for energy savings in industrial electric motors as a function of motor output power (installed capacity multiplied by the average efficiency improvement)

replaced that adopted (categories Eff1, Eff2, and Eff3) by agreement with CEMEP (European Committee of Manufacturers of Electrical Machines and Power Electronics):

	CEMEP/EU agreement	Regulation 640/2009
Number of poles:	2 or 4	2, 4, or 6
Voltage and frequency:	400 V, 50 Hz	<1,000 V, 50/60 Hz
Power range:	1.1 to 90 kW	0.75 to 375 kW
Efficiency levels:	Eff3 – Standard efficiency	IE1 – Standard efficiency
	Eff2 – Improved efficiency	IE2 – High efficiency
	Eff1 – High efficiency	IE3 – Premium efficiency

Different alternatives have been used to apply the life cycle analysis (LCA) method to electrical equipment (Croezen and Bello 2003; Deprez et al. 2006; De Keulenaer et al. 2006) and even ABB has used the method Environmental Product Declaration based on the international standards ISO 14040–43 (ABB 2005). Nevertheless, the Methodology for the Ecodesign of Energy Using Products (MEEUP) was employed, in the cited report EUP Lot 11 Motors, to assess the environmental impact of electric motors. This methodology is based on the use of a spreadsheet in which LCA is applied to a set of data basically comprising the quantity of each material used to manufacture the motor, and the electrical energy that the motor consumes during the service life phase (according to its power and efficiency). In the spreadsheet, the environmental impact ratios outlined in the document MEEUP 2005 are applied.

In the work reported here, the MEEUP methodology was applied to two different three-phase induction motors of 1.5 kW of rated power, because they are a standard base case in the lower power range in the industry and tertiary sector (examples of application can be found in small pumps, fans, compressors, and conveyors). The influence of each design parameters was assessed for its contribution

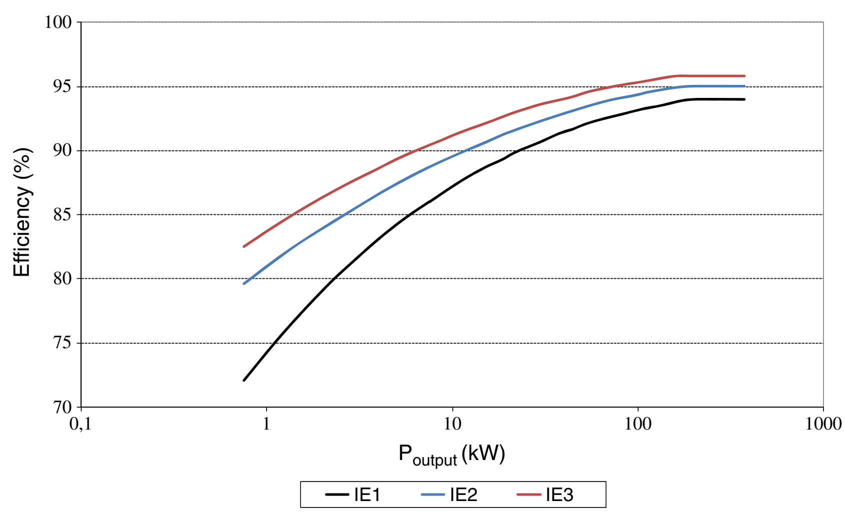


Fig. 2 Efficiency vs. output power of three efficiency categories for four-pole, 50 Hz motors

to the environmental impact of each motor. These real motors were then compared to a proposed motor designed in terms of performance and environmental impact.

2 Calculation procedure

This section describes the calculation procedure developed to determine the parameter values needed to apply the MEEUP methodology to the two motors to determine their environmental impact (Fig. 3). This methodology is based on European regulations, and is designed for assessment of the environmental impact of energy using products in function of their production, distribution, service life, recycling, and waste disposal. The methodology should follow, not precede current environmental guidelines established in international treaties and enacted in appropriate EU legislation. The tools for assessing the environmental impact were based on accepted scientific principles and the data were collected from industry associations, EC reports and environmental studies from companies. MEEUP (2005)) methodology is a simple method implemented in a spreadsheet that comprises the main following parts:

1. Inputs (bill of materials, inclusively energy necessary in the production process; performance, energy consumption, and emission characteristics during the service life phase; volume of package final product; recycling and waste disposal).
2. Results presented as a list of environmental indicators (total cumulative primary energy, water, waste, global warming potential, acidification emissions, heavy metals, particulate matter, eutrophication potential…).

According to this procedure, one motor corresponds to efficiency category IE1, and the other, to IE2. The bill of materials from manufacturing of each motor was known. Lastly, both motors were laboratory tested to determine their efficiency according to standard IEC 60034-2-1 (IEC 60034-2-1 2007), using the summation of losses method.

Calculation entailed the following steps:

1. Compiling the initial motor data

   The following manufacturer's data were used:

   – Rated output power (P_{out})
   – Rated voltage (V_1)
   – Synchronous speed (n_s)
   – Frequency (f)
   – Number of poles ($2p$). (p is used to indicate the number of the pair of poles)

2. Selecting the design parameters

   The following parameters were chosen:

   – Airgap diameter (D)
   – Stack length (L)
   – Specific electric loading (q)
   – Airgap flux density (B)
   – Stator and rotor current densities (Δ_1 and Δ_2, respectively)

3. Determining the amount of each material used in manufacturing

   The principal constituents of each motor were quantified as follows:

   – Magnetic lamination material mass (W_{Fe})
   – Copper mass (W_{Cu})
   – Aluminum mass (W_{Al})
   – Steel mass (W_{steel})

4. Determining input power, losses, and efficiency

   Based on the aforementioned design parameters and material quantities, the input power (P_{in}), different losses (listed below), and the efficiency (η) of each motor were calculated using Eqs. 1–9 (Boldea and Nasar 2002; Hamdi 1994; Pyrhönen et al. 2008). The studied losses comprise: stator copper losses (P_{j1}), rotor

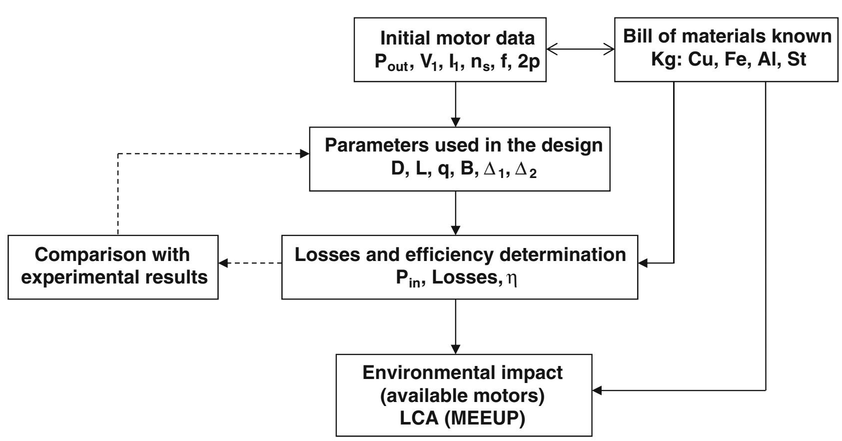


Fig. 3 Calculation procedure applied to the available two motors

copper losses (P_{j2}), iron losses (P_{fe}), mechanical losses (P_{mec}), and stray load losses (P_{SLL}).

$$P_{in} = 0.1165\, D^2\, \mathrm{L\, q\, B\, n_s}\, \xi_1 \tag{1}$$

where ξ_1 is the stator winding factor

$$P_{j1} = \frac{\rho_{cu}\, W_{cu}\, \Delta_1^2\ 10^6}{\gamma_{cu}} \tag{2}$$

where

ρ_{cu} resistivity of copper (Ohm-square millimeter per meter)
γ_{cu} density of copper (kilogram per cubic meter)

$$P_{j2} = \frac{\rho_{al}\, W_{al\,(rotor)}\, \Delta_2^2\ 10^6}{\gamma_{al}} \tag{3}$$

where

ρ_{al} resistivity of aluminum (Ohm-square millimeter per meter)
γ_{al} density of aluminum (kilogram per cubic meter)

(the current density in the rotor bars and in the end-ring of the squirrel-cage winding were considered to be equal)

$$P_{fe} = W_{fe(teeth)} \times \left[\left(\sigma_h\ \mathrm{f}\ \widehat{B}_t^2 10^{-2}\right) + \left(\sigma_{ed}\ \mathrm{e}^2 \mathrm{f}^2 \widehat{B}_t^2 10^2\right)\right] + \\ + W_{fe(yoke)} \times \left[\left(\sigma_h\ k_h\ \mathrm{f}\ \widehat{B}_y^2 10^{-2}\right) + \left(\sigma_{ed}\ k_e\ \mathrm{e}^2\ \mathrm{f}^2\ \widehat{B}_y^2 10^2\right)\right] \tag{4}$$

where

B_t, B_y flux density in the teeth and in the yoke, respectively (the following approaches were assumed: B_t=2 B and B_y=1.5 B)
σ_h hysteresis specific losses coefficient of magnetic lamination material
σ_{ed} eddy current specific losses coefficient of magnetic lamination material
e lamination thickness (meter)
k_h, k_e hysteresis and eddy current loss coefficients due to uneven flux distribution in the yoke

$$P_{mec} = [0.15\, n_s\, D_{sh}^3\, 10^3\, n_c] + [\frac{1}{1,500}\, P_{losses}\, (\frac{\pi D\, n_s}{60})^{2.25}] \tag{5}$$

where

D_{sh} shaft diameter (meter)
n_c bearing number
P_{losses} total losses (W)

The stray load losses (P_{SLL}) are assigned as an input power percentage according to the rated output power, as indicated in standard IEC60034-2-1:

$$\begin{array}{ll} P_{out} \le 1\mathrm{kW} & P_{SLL} = P_{in} \cdot 0.025 \\ 1\mathrm{kW} < P_{out} \le 10,000\mathrm{kW} & P_{SLL} = P_{in} \cdot [0.025 - 0.005 \log 10\, (P_{out}/1\mathrm{kW})] \\ P_{out} > 10,000\mathrm{kW} & P_{SLL} = P_{in} \cdot 0.005 \end{array}$$

The efficiency was calculated using Eq. 6.

$$\eta = \frac{P_{out}}{P_{in}} = \frac{P_{in} - P_{j1} - P_{j2} - P_{fe} - P_{mec} - P_{SLL}}{P_{in}} \tag{6}$$

The stator winding characteristics were defined from the following equations:

$$Z = \frac{0.0045\ V_1\, 2\mathrm{p\, m}}{\xi_1\, \mathrm{D\, L\, B}} \tag{7}$$

$$I_1 = \frac{\pi\, \mathrm{D\, q}}{Z} \tag{8}$$

$$s_c = \frac{I_1}{\Delta_1} \tag{9}$$

where

Z number of stator wire
m phases number
I_1 stator phase current
s_c stator wire area

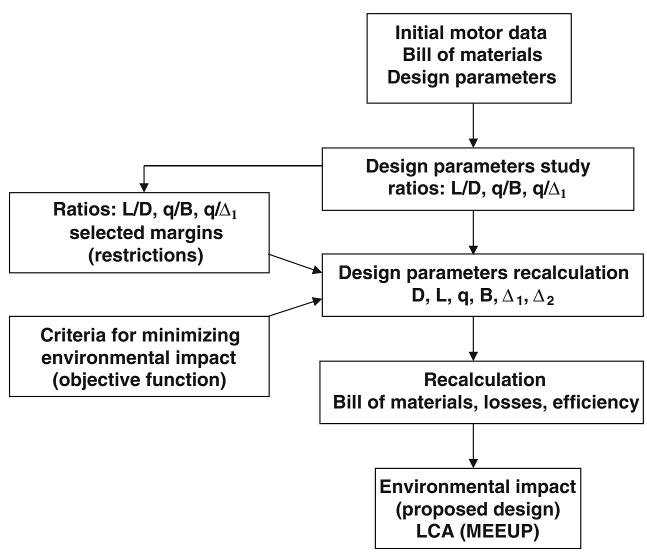


Fig. 4 Calculation procedure developed for minimizing environmental impact

Table 1 Design parameter values in the IE1 motor, the IE2 motor, and the proposed motor

	D (m)	L (m)	q^{a} (A/m)	B^{a} (T)	$\Delta_1{}^{a}$ (A/mm^2)	$\Delta_2{}^{a}$ (A/mm^2)
IE1	0.0835	0.1	21,000	0.8	6.2	5
IE2	0.082	0.125	16,500	0.8	5.2	4.3
Proposed	0.0943	0.0754	18,000	0.9	5	4

[a]Estimated values

5. Comparing the calculated values to the laboratory tests results

   The two motors were tested to determine their respective losses and efficiency, according to standard IEC60034-2-1. The laboratory tests necessary for summation of motor losses comprise:

   – Measurement of stator resistance.
   – A no-load test, at seven different voltages (including the rated voltage).
   – A load test, at six different loads (including the rated load).

6. Evaluating environmental impact

   As previously mentioned, an MEEUP methodology was employed to assess the environmental impact of each motor. This required the following data for each motor:

   – The bill of materials from manufacturing.
   – The operating hours per year, the life cycle length (in years), and the operating load.
   – The output power and efficiency at the operating load considered.

3 Design parameters studied for environmental impact

To minimize the environmental impact of each motor, the calculation procedure indicated in Fig. 4 was applied. The design parameters of the motor were selected based on the following ratios:

a. L/D (at a fixed value of $D^2{\cdot}$L)
b. q/B (at a fixed value of $q{\cdot}$B)
c. q/Δ_1 (at a fixed value of $q{\cdot}\Delta_1$)

This study was used to establish the margin in which the ratios L/D, q/B, and q/Δ_1 would provide optimal operation (in terms of environmental impact). This margin was also employed as a restriction in a non-linear program that was developed (see below). By varying the values of the design parameters, the material quantities for the motor manufacturing were calculated from Eqs. 10–13.

$$W_{\mathrm{Fe}}{}' = \left[W_{\mathrm{Fe(stator)}}\frac{D'^2L'}{D^2L}\right] + \left[W_{\mathrm{Fe(rotor)}}\frac{\left(D'^2 - D_{\mathrm{sh}}^2\right)L'}{\left(D^2 - D_{\mathrm{sh}}^2\right)L}\right] \tag{10}$$

$$W_{\mathrm{Cu}}{}' = W_{\mathrm{Cu}}\frac{q'\,D'\,\mathrm{L}'\,\varDelta_1}{q\,D\,\mathrm{L}\,\varDelta_1'} \tag{11}$$

$$W_{\mathrm{Al}}{}' = \left[W_{\mathrm{Al(rotor)}}\frac{q'\,\mathrm{D}'\,\mathrm{L}'\,\varDelta_2}{q\,\mathrm{D}\,\mathrm{L}\,\varDelta_2'}\right] + \left[W_{\mathrm{Al(enclosure)}}\frac{(\mathrm{D}' + \mathrm{h})\mathrm{L}'}{(\mathrm{D} + \mathrm{h})\mathrm{L}}\right] \tag{12}$$

$$W_{\mathrm{steel}}{}' = W_{\mathrm{steel}}\frac{L'}{L} \tag{13}$$

where h = width of the enclosure

To minimize the environmental impact, a non-linear optimization program was developed based on the margins selected for the ratios L/D, q/B, and q/Δ_1. The program, which can be solved using the "Solver" function in Microsoft Excel, is structured as follows:

Objective function:
Minimize the environmental impact
Parameters to calculate:
L, D, q, B, Δ1
Restrictions:

$$0.8 \le L/D \le 1.6$$
$$15,000 \le q/\mathrm{B}(\mathrm{A/T\,m}) \le 30,000$$
$$2,600 \le q/\varDelta_1\left(\mathrm{mm}^2/\mathrm{m}\right) \le 3,600$$
$$P_{\mathrm{out}} = P_{\mathrm{out}}\,\text{rated} \pm 5\%$$

Table 2 Material quantities used in manufacturing and type of the magnetic lamination used in the IE1 motor, the IE2 motor, and the proposed motor

	W_{Fe} (kg)	W_{Cu} (kg)	W_{Al} (kg)	W_{steel} (kg)	Magnetic lamination
IE1	7.8	1.875	3.93	2.25	M800-50A
IE2	9.15	2.175	4.35	2.81	M530-50A
Proposed	7.41	1.71	3.05	1.69	M400-50A

Table 3 Input and output power, losses, and efficiency in the rated operation in the IE1 motor, the IE2 motor, and the proposed motor

	P_{out} (W)	P_{in} (W)	η	P_{j1} W (%)	P_{j2} W (%)	P_{fe} W (%)	P_{mec} W (%)	P_{SLL} W (%)
IE1 (calc.)	1,519.7	1,944.5	0.7815	174.2 (41.01)	102.6 (24.15)	80.6 (18.97)	30.2 (7.11)	37.2 (8.76)
IE1 (test)	1,539	1,970	0.7812	193.2 (44.82)	94.6 (21.96)	73.6 (17.08)	32.2 (7.47)	37.4 (8.67)
IE2 (calc.)	1,518	1,849.4	0.8201	142.1 (42.87)	84.1 (25.38)	44.4 (13.39)	25.6 (7.73)	35.2 (10.63)
IE2 (test)	1,509	1,843	0.8188	133.2 (39.88)	86.2 (25.81)	38.7 (11.58)	34.6 (10.37)	41.3 (12.36)
Proposed	1,555	1,796.9	0.8653	102.7 (42.45)	58.9 (24.35)	20.8 (8.60)	25.2 (10.42)	34.3 (14.18)

The spreadsheet for solving the above optimization program incorporates Eqs. 1–13, as well as the environmental impact ratios employed for the MEEUP methodology in the LCA.

4 Results and discussion

Table 1 shows the parameter values for the two real motors and the proposed motor. Table 2 shows the material quantities used in manufacturing of the two real motors, and the magnetic lamination used, as well as the corresponding data for the proposed design. The material quantities indicate in the Table 2 are shown in the total mass value (kilogram) and the specific losses of magnetic lamination materials are, at 50 Hz–1.5 T: 8 W/kg (M800-50A), 5.3 W/kg (M530-50A), and 4 W/kg (M400-50A).

The values for the real motors were calculated using the procedure indicated in Fig. 3 (Andrada et al. 2009; Jardot et al. 2010), whereas those for the proposed design were obtained using the procedure indicated in Fig. 4.

The initial values for the two studied motors were: output power, 1.5 kW; voltage, 230 V; synchronous speed, 1,500 rpm; frequency, 50 Hz; number of poles, four; and efficiency category, IE1 (one motor) or IE2 (the other one).

The results for the proposed design in terms of design variables selected and the material quantities used are also indicated in these tables, according to the calculation procedure indicated in Fig. 4, applying the optimization program in the same type of the studied motors.

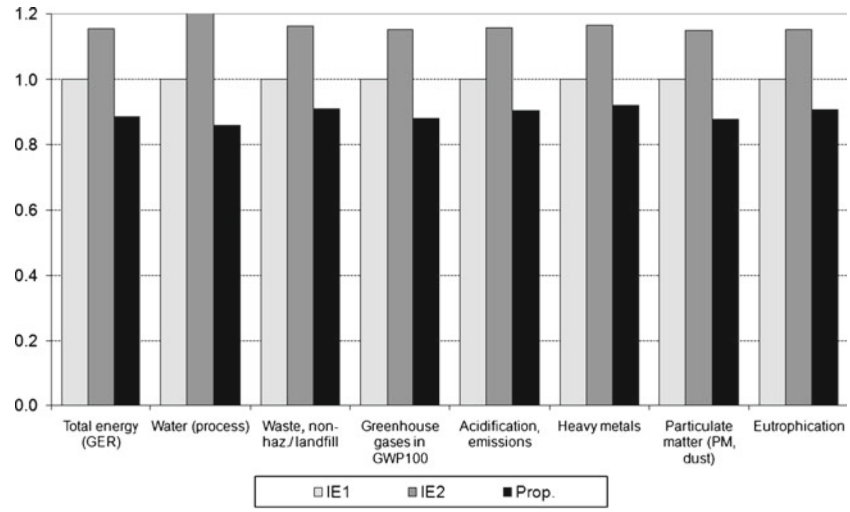
Table 3 shows the calculated and the laboratory test values of the input power, output power, losses, and efficiency for the two real motors, plus the corresponding calculated values for the proposed motor. The calculated values and the laboratory test results were compared according to standard IEC60034-2-1.

As revealed by Table 3, the calculation procedure was deemed satisfactory. The values for material quantities (see Table 2) were used to assess the environmental impact of each motor in the production phase, and the values for powers and efficiency (see Table 3) were used to assess the environmental impact of each motor in the service life phase (considering 4,000 h of operation per year, a life cycle of 12 years, and operation at full load). Lastly, the end-of-life environmental impact was evaluated for each motor based on its potential for materials recycling. The distribution phase was not considered, because it is practically identical for both motors (the mass of the tree motors is very similar although not exactly, but the box to transport is the same). The overall results for the IE1 motor, the IE2 motor and the proposed motor are shown in Table 4. A relative comparison of environmental impact between the IE1, the IE2, and the proposed motor is shown in Fig. 5 (Martínez et al. 2009).

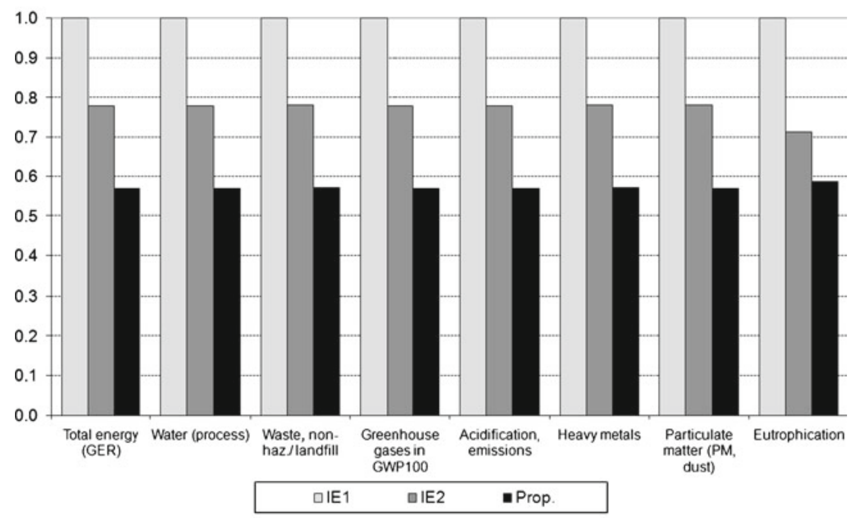
Table 4 Total environmental impact of the IE1 motor, the IE2 motor, and the proposed motor (these data are obtained directly by the spreadsheet that incorporate the values for the MEEUP application)

	Unit	IE1	IE2	Proposed
Resources and waste				
Total energy (GER)	MJ	215,246	168,332	122,974
Water (process)	L	14,278	11,140	8,134
Waste, non-haz./landfill	g	306,449	261,356	194,333
Emissions (air)				
Greenhouse gases in GWP100	kg CO_2 eq.	9,419	7,375	5,389
Acidification, emissions	g SO_2 eq.	55,915	43,912	32,111
Heavy metals	mg Ni eq.	3,887	3,114	2,289
Particulate matter (PM, dust)	g	1,369	1,129	847
Emissions (water)				
Eutrophication	g PO_4	8.07	7.03	5.02

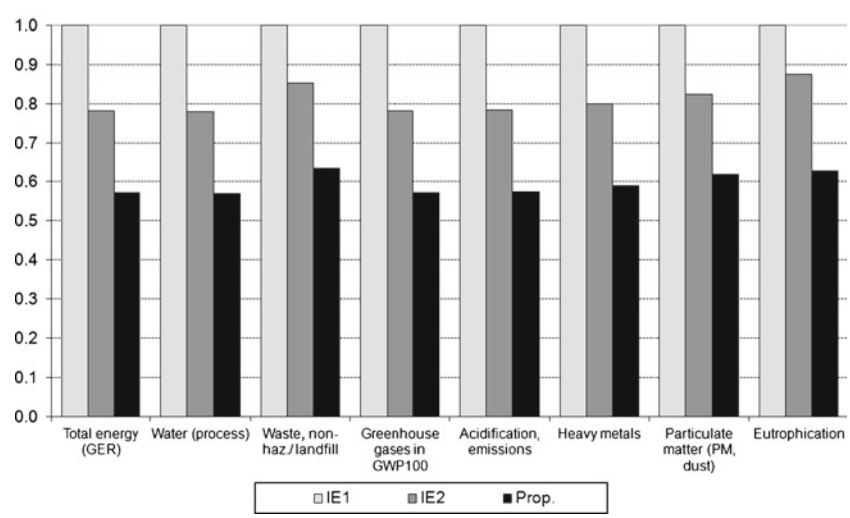
Fig. 5 Relative comparison of the environmental impact of the IE2 motor and of the proposed motor to that of the IE1 motor in the production phase, service life phase, and total



a) Production phase



b) Service life phase



c) Total

The total environmental impact of IE2 motor is far lower than the IE1 motor due to its higher efficiency (efficiency is highly influential in the service life phase, which is the most important phase for dictating environmental impact). The higher efficiency in IE2 comes at the expense of using more materials namely, better quality magnetic lamination; therefore, the IE2 motor has greater environmental impact in the production phase. The IE2 motor has higher efficiency than IE1 motor due to the use of more conductor materials and more magnetic lamination although of less specific losses. In the proposed design, the section of conductors can be enlarged and shortened its length, due to the increase of the air gap diameter and the reduction of the stack length. Therefore, there is a reduction of the conductor materials (copper and aluminum) and as a consequence of the Joule losses. These changes also reduce the amount of magnetic lamination, which combined with the use of materials with lower specific losses, lead to a reduction of iron losses.

In terms of efficiency, the proposed motor would be an IE3 motor (according to standard IEC60034-30). Furthermore, it would need less material for manufacturing, but would require a magnetic lamination with slightly higher values of flux density and lower specific losses than in IE2. Although the input power (P_{in}) in the proposed motor is 2.83% lower than IE2 motor and 7.59% lower than IE1 motor, its total losses are reduced a 27% respect to the IE2 motor and a 43% to IE1 motor; therefore, for the same output power, it is possible to obtain a higher efficiency.

5 Conclusions

Using a MEEUP methodology is a good strategy for assessing the environmental impact of electric motors in different life cycle phases. The greatest environmental impact phase typically derives from the service life phase, such that a motor's efficiency will be the greatest determinant of its overall environmental impact. The parameter values chosen during the design of a motor, will determine the material quantities used and will determine its efficiency. Thus, the design phase is an essential stage for minimizing environmental impact. Indeed, a comprehensive study on the environmental influence of these parameters can provide major environmental benefits, for both the production phase and the service life phase. Using materials with improved functional performance (e.g., in this case, magnetic lamination material with lower specific losses) that enable higher flux densities can enable significant reductions in environmental impact during the life cycle of an electric motor.

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